Parameterizing the Effects of Upper-Ocean Large Eddies
on Air-Sea Interaction

Ming Li
Horn Point Laboratory
University of Maryland Center for Environmental Science
2020 Horn Point Road, Cambridge, MD 21613
Phone: 410-228 8420 Fax: 410-228 8490 Email: mingli@hpl.umces.edu

Chris Garrett
School of Earth and Ocean Sciences
University of Victoria
P.O. Box 3055, Victoria, B.C. Canada, V8W 3P6
Phone: 250-721 7702 Fax: 250-721 7715 Email: garrett@phastf.phys.uvic.ca

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LONG-TERM GOALS

To understand the effects of upper-ocean turbulent processes on air-sea interaction and obtain improved parameterization of these processes for use in large-scale ocean models.

OBJECTIVES

There are two primary objectives in this CBLAST modeling project. First, we seek to understand the dynamics of upper-ocean large eddies which play a critical role in the air-sea exchange and obtain physics-based parameterizations of momentum, energy and heat fluxes in the ocean surface boundary layer. Second, we seek to understand and interpret upper-ocean measurements acquired during the CBLAST field experiments.

APPROACH

Our approach is to combine process-oriented numerical modeling studies in nondimensional parameter space with simulations and interpretations of upper-ocean data obtained from the CBLAST field programs. In process studies, we identify a set of controlling nondimensional parameters and explore the model results in the parameter space. By doing this, we hope to see the dynamic processes in perspective and develop robust parameterization schemes. In data simulations, we collaborate with the field investigators conducting both CBLAST low and hurricane experiments.

WORK COMPLETED

We have conducted a large number of process-oriented LES simulations of upper-ocean turbulent processes over a broad range of forcing conditions. We have completed the analysis of turbulent dynamics in an initially homogeneous mixed layer and obtained interesting preliminary results on the interaction between the large eddies and pre-existing stratification.

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We have adapted the LES model to run hindcast simulations of field experiments. We have not had an opportunity to simulate the observations collected during the recent CBLAST-Low main experiment. However, we have run the simulations for open-ocean observations collected during a previous field experiment funded by ONR (in collaboration with Dr. Farmer at URI). This has provided us valuable experience for running simulations for the CBLAST experiments.

RESULTS

Wave-driven Langmuir circulation, buoyancy-driven thermal convection and shear-driven Kelvin-Helmholtz billows are the dominant large eddies in the ocean surface boundary layer. We have examined how they compete to generate turbulence in an initially well-mixed layer. By nondimensionalizing the LES equations, we have identified two controlling dimensionless numbers: (1) Hoenikker number *Ho* (Li & Garrett, 1995, JPO) is a ratio of buoyancy force to vortex force; (2) turbulent Langmuir number La_t (McWilliams et al. 1997, JFM) is a ratio of the water friction velocity to the Stokes drift velocity. We have carried out a systematic investigation into the dynamics of the large eddies in $La_t - Ho$ parameter space. In the report submitted last year, we showed some preliminary results. We have now completed this modeling study and are writing it up for publication.

The main results are summarized in the regime diagram shown in Figure 1. It is based on the depth-averaged vertical velocity variance normalized by the square of the friction velocity. In a horizontal slice through the parameter space at Ho=0 (no heat flux across the sea surface), turbulence changes from the shear type to Langmuir type as the turbulent Langmuir number La_t decreases (wave forcing increases). There is a rapid transition between the two regimes. In a vertical slice at La_t=0.34 through the parameter space, turbulence changes from the Langmuir type to convective type as Ho increases (more heat loss at the sea surface). In Figure 1 we have chosen a nonlinear scale in marking the contours. As one can see, there is little change in the flow index in the lower right part of the parameter space. In this shear regime, the vertical velocity variance is scaled by the friction velocity. Moving towards the left and upwards, we see a steep gradient, which we have marked it as a dividing line. We can further divide the left domain into two regions by a selecting a line of Ho at which the vertical velocity variance doubles that when Ho=0. The region below the line is Langmuir regime whereas the region above the line is convective regime. For realistic oceanic values, one has parameter values close to La_t=0.3 and Ho=0.01. This would put a typical oceanic condition inside the Langmuir regime. Of course, when the wind is weak, Ho will be large so that the ocean will be in the convective regime as one expects under the nighttime cooling condition.

The three types of large eddies identified in the regime diagram have distinctive properties in low-order turbulence statistics. For example, the ordering of turbulence intensities in three directions is different. In the shear turbulence, the downwind component is the largest one, $<u'^2>$ (downwind) **>** $<v'^2>$ (crosswind) **>** $<w'^2>$(vertical). In langmuir turbulence, however, the crosswind component is the largest and downwind component the smallest, $<v'^2>$ **>** $<w'^2>$ **>** $<u'^2>$. In the convective regime, the vertical component is larger than the two horizontal components, $<w'^2>$ **>** $[<u'^2>,<v'^2>]$. Such different ordering of turbulence intensities can be explained by examining the three components of the turbulent kinetic energy equation. In the shear-driven turbulence, shear production directly injects turbulent energy into the downwind component, which is redistributed to the other two components by pressure and turbulent transport terms. In convection, buoyancy force generates turbulence energy in the vertical direction, which is then redistributed to the two horizontal components by transport terms. In Langmuir turbulence, shear production is reduced because the

mean flow is homogenized, but the stokes production due to surface waves generates turbulence energy in both crosswind and vertical directions.

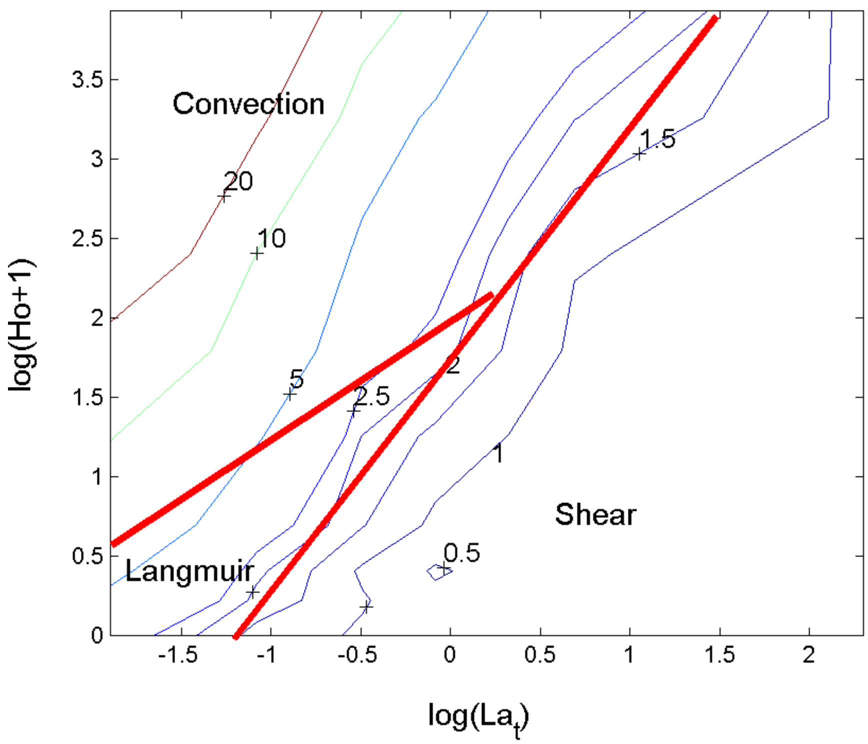

Figure 1. A regime diagram to differentiate convective, shear and Langmuir turbulence in the ocean surface boundary layer. The diagram is plotted over log(La_t) and log(Ho+1) coordinates to better visualize the results. In the shear regime, turbulence intensity is scaled by the friction velocity. In the Langmuir regime, the ratio of turbulence intensity to friction velocity increases as La_t decreases. A typical ocean condition with wind speed of 10 m/s, a fully-developed sea state and a surface heat loss rate of –200 W/m^2 corresponds to La_t=0.3 and Ho=0.01 in the Langmuir regime.

A problem of critical importance to air-sea interaction is how the turbulent large eddies erode the stratification and redistribute water properties in the ocean surface layer. We have examined how shear and Langmuir turbulence erodes a linearly stratified water (with buoyancy frequency *N*). There are two controlling dimensionless parameters. One is the turbulent Langmuir number La_t. Another one is identified to be $R_{LN} = N^2/(u_*^2\beta^2)$ which compares the strength of stabilizing buoyancy force to the wind shear. Figure 2 shows the results from two numerical experiments. Run 1 (Figures 2a-c) corresponds to La_t =0.34 and R_{Ln} =0.15 typical of Langmuir turbulence. Vigorous mixing quickly generates a surface mixed layer, as cold water is engulfed from below by upwelling plumes. Because of the effective momentum and tracer transport in Langmuir turbulence, both the mean velocity and mean temperature profiles become nearly uniform within the mixed layer. Run 2 (Figures 2d-f) corresponds to La_t =1.76 and R_{Ln} =0.22 typical of shear turbulence. The deepening of the mixed layer is slower and is caused by Kelvin-Kelmholtz billows. Significant shear remains in the mean velocity profile. The mean temperature profile also shows a more gradual change. These numerical experiments highlight two different mechanisms for mixed-layer deepening. In Langmuir turbulence, the deepening occurs through direct engulfment of stratified water into the mixed layer. In shear

turbulence, the deepening occurs through the shear instability. We are using the LES result to test two different parameterization scheme: one based on the PWP bulk Richardson number criterion and another one based on the 2D DNS results of Li & Garrett (1997, JPO).

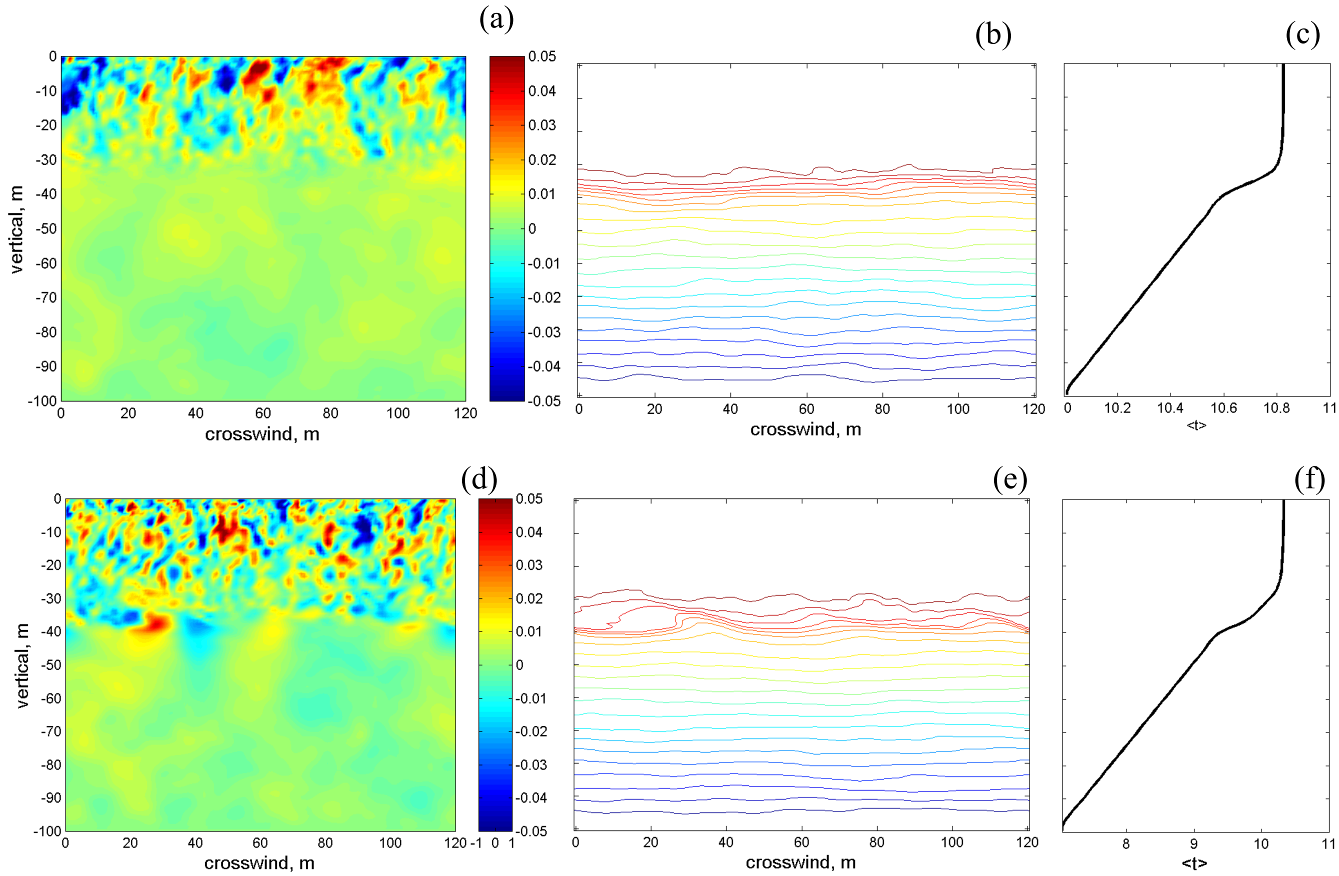

Figure 2. Deepening of the mixed layer into a linearly stratified water by Langmuir (a-c) and shear (d-f) turbulence. Vertical velocity distribution (a, d) and contours of temperature (b, e) in a crosswind section, vertical profiles of mean temperature (c, f). In Langmuir turbulence, upwelling plumes engulf stratified water into the mixed layer. In shear turbulence, Kelvin-Kelmholtz billows cause the deepening of the mixed layer.

In preparation for simulating CBLAST experiments, we have conducted hindcast simulations of a wind event in the open ocean of North Pacific, as shown in Figure 3. We have run the model over a two-day period in November 1997, when the wind speed gradually picked up and a suite of upper-ocean measurements took place. Figure 4b shows a scanning image of horizontal distribution of bubble clouds illustrating their characteristic organization into structures roughly aligned with the wind (Farmer et al., 2001). Figure 4a is the LES simulation using the observed forcing parameters such as wind speed, surface drift and e-folding depth of the Stokes drift current, and surface heat fluxes. The model is initialized with vertical profiles of temperature and salinity obtained from the CTD casts. Near-surface vertical velocity field shown in Figure 4a reveals alternating upwelling and downwelling flows, which correspond to divergence and convergence zones at the ocean surface. Buoyant bubbles detected in sonar images are collected at the convergence zones. A comparison between figure 4a and 4b demonstrates an excellent agreement between the LES model simulations and sonar observations.

Furthermore, the modeled temperature anomalies are also in good agreement with the fine-resolution temperature measurements obtained from thermistor chains.

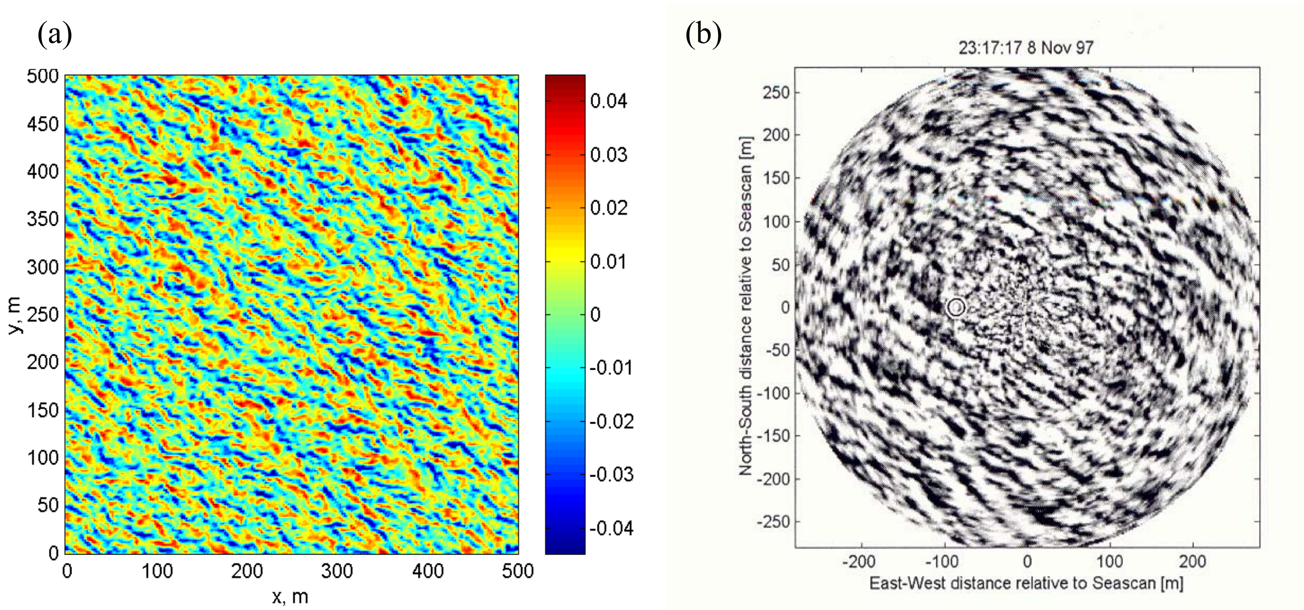

Figure 3. A comparison between LES model predictions and sonar image of upper-ocean bubble clouds obtained during a storm in the North Pacific. (a) Near-surface distribution of vertical velocity. Downwelling bands correspond to convergence zones where bubbles converge. (b) An image of surface bubble clouds obtained from rotating sidescan sonars.

IMPACT/APPLICATIONS

Our modeling investigations into the upper-ocean turbulence dynamics will contribute to a better understanding of air-sea interaction and help interpret CLBAST field observations.

RELATED PROJECTS

We collaborate with Bob Weller, John Trowbridge, Al Plueddeman and Jim Edson on interpreting data from CBLAST-Low experiments and Eric D'Asaro on interpreting data from CBLAST-Hurricane experiments. In July 2003, Ming Li gave a seminar at WHOI and discussed the model/data comparison with CBLAST-Low investigators.